On The Recently Discovered Correlations Between Gamma-ray And X-ray Properties Of Gamma Ray Bursts

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ABSTRACT

Recently, several new correlations between the observed γ-ray and the X-ray properties of gamma-ray bursts (GRBs) were inferred from a comprehensive analysis of the X-ray light curves of more than 650 GRBs measured with the Swift X-ray telescope (Swift/XRT) during the years 2004-2010. Like previously well established correlations, they challenge GRB models. Here we show that in the cannonball (CB) model of GRBs, the newly discovered correlations and those that follow from them, have the same simple kinematic origin as those discovered earlier. They result from the strong dependence of the observed radiations on the bulk motion Lorentz and Doppler factors of the jet of highly relativistic plasmoids (CBs) that produces these radiations by interaction with the medium through which it propagates.

Subject headings: (Stars:) gamma-rays: bursts

1. Introduction

As the measurements of the properties of gamma ray bursts (GRBs) and their afterglows (AGs) become more complete and more accurate, new correlations between these properties are being discovered. Such correlations challenge GRB models. Recently Margutti et al. (2013) reported results from a comprehensive statistical analysis of the X-ray light-curves of more than 650 GRBs (GRBs) measured with the Swift X-ray telescope (Swift/XRT) between 2004 and the end of 2010. In particular, they reported the discovery of new correlations between the properties of the γ-ray and the X-ray emission in GRBs. In this paper we show that the newly discovered correlations by Margutti et al. (2013) between the γ-ray and X-ray properties of GRBs, after correcting for biases and eliminating the peculiar GRB 060218 (Soderberg et al. 2006) from their selected sample of GRBs with known redshift, agree well with those predicted by the cannonball (CB) model of GRBs (Dar & De Rújula 2004, Dado

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et al. 2009a,b and references therein). Like the previously well established correlations between GRB observables, they all have the same simple kinematic origin - they result from the strong dependence of the observed radiations on the bulk motion Lorentz and Doppler factors of the jet of highly relativistic plasmoids (CBs) that produces the radiations by its interaction with the medium through which it propagates (Dar and De Rújula 2000,2004, Dado et al. 2007, Dado and Dar 2012a).

2. Origin of the observed radiations in the CB model

In the cannonball (CB) model of GRBs (Dado et al. 2002, Dar and De Rújula 2004, Dado et al. 2009a,b) GRBs and their afterglows are produced by the interaction of bipolar jets of highly relativistic plasmoids (CBs) of ordinary matter with the radiation and matter along their trajectory (Shaviv and Dar 1995, Dar 1998). Such jetted CBs are presumably ejected in accretion episodes on the newly formed compact stellar object in core-collapse supernova (SN) explosions (Dar et al. 1992, Dar and Plaga 1999, Dar and De Rújula 2000), in merger of compact objects in close binary systems (Goodman et al. 1987, Shaviv and Dar 1995) and in phase transitions in compact stars (Dar 1998, Dar and De Rújula 2000, Dado et al. 2009b). For instance, in GRBs produced in SNe, it is hypothesized that an accretion disk or a torus is produced around the newly formed compact object, either by stellar material originally close to the surface of the imploding core and left behind by the explosion-generating outgoing shock, or by more distant stellar matter falling back after its passage (Dar and De Rújula 2000, 2004). As observed in microquasars, each time part of the accretion disk falls abruptly onto the compact object, two CBs made of ordinary-matter plasma are emitted with large bulk-motion Lorentz factors $\gamma \gg 1$ in opposite directions along the rotation axis from where matter has already fallen back onto the compact object due to lack of rotational support. The prompt γ-ray pulses and early-time X-ray flares are dominated by inverse Compton scattering (ICS) of glory photons - a light halo surrounding the progenitor star that was formed by stellar light scattered from the pre-supernova wind blown from the progenitor star. The ICS is overtaken by synchrotron radiation (SR) when the CB enters the pre-supernova wind/ejecta of the progenitor star. The fast decline of the prompt emission with a fast spectral softening is overtaken (see, e.g., Dado et al. 2007, 2009a) by a broad-band SR afterglow with a much harder spectral index that stays constant in the X-ray band, $\beta_X \simeq 1$, when the CB propagates in the wind and interstellar (ISM) environment. ICS of the SR produces the emission of very high energy photons during the early time optical/NIR emission and the broad band afterglow (Dado and Dar 2009c).

3. Correlated γ-ray and X-ray properties

GRBs are not standard candles because of the diversity of their central engines and environments. But, because of the large bulk motion Lorentz factor γ of the jet of CBs, their emitted radiation at redshift z, which is observed at a small angle θ relative to the direction of the jet, is boosted by a large Doppler factor $\delta = 1/\gamma\,(1-\beta\, cos\theta)$ and collimated through relativistic beaming by a factor δ^2. The large Doppler boosting, relativistic collimation and time aberration dominate the GRB properties and produce correlations between GRB observables (Dar and De Rùjula 2000, 2004, Dado and Dar 2012a), despite their dependence on the CBs' intrinsic (rest frame) properties and on the environment along their trajectories (which produce a significant spread around these simple kinematic correlations).

The redshift z of the GRB location is measurable, and the dependence of the GRB observables on redshift can be taken into account explicitly, unlike their dependence on the values of the Lorentz factor and the viewing angle of the jet, which can only be inferred with model-dependent assumptions. However, several observables depend on the same combination of γ and δ that result in pair correlations. For instance, in the CB model, Δ the full width at half maximum, t_r the rise-time from half maximum to maximum, and t_f the fall-time from maximum to half maximum in *every prompt emission pulse* are all proportional to $(1+z)/\gamma\,\delta$ while their peak energy E_p is proportional to $\gamma\,\delta/(1+z)$, yielding the correlations $t_r \propto t_f \propto \Delta \propto 1/E_p$ *for each individual peak* (Dar & De Rujula 2000, 2004). Moreover, due to selection effects in the observations, various observables depend strongly only on γ or δ, which also yields pair-correlations. In particular, the dependence on viewing angle of the jet can be eliminated in two general cases: For $\gamma^2 \gg 1$ and small viewing angles $\theta^2 \ll 1$, the Doppler factor satisfies $\delta \approx 2\,\gamma/(1+\gamma^2\,\theta^2)$ to an excellent approximation. In ordinary GRBs, $\theta^2\,\gamma^2 \simeq 1$ and $\delta \sim \gamma$. In GRBs viewed far-off axis, i.e., $\gamma^2\,\theta^2 \gg 1$, such as X-ray flashes (XRFs), the dependence on the exact value of the Lorentz factor can be neglected compared to that on the Doppler factor. These two situations yield slightly different correlations in ordinary energetic GRBs and in soft GRBs and XRFs. Moreover, the correlations depend on whether the CBs are emitted along a single direction (assumed in most of our papers on GRBs) or in a 'shot gun' configuration (Dado & Dar 2012b). Thus, for a mixed population of ordinary GRBs and XRFs we shall approximate their slightly different correlations by a single power-law correlation with their mean power-law index and an uncertainty implied by the unknown viewing angles.

Below we demonstrate the use of the dependence of γ-ray and X-ray properties of GRBs on the Lorentz and Doppler factors to derive the observed kinematic correlations between them in the observer frame and/or the GRB rest frame (indicated by a prime).

4. Correlations between γ-ray properties

In the CB model, the prompt emission is a sum of individual pulses. In *each pulse*, the peak energy E_p of the time-integrated spectral energy flux, the total gamma-ray energy emission under the assumption of isotropic emission $E_{\gamma,iso}$ and the peak luminosity $L_{p,\gamma}$ satisfy $E_{\gamma,iso} \propto \delta^3$ and $L_{p,\gamma} \propto \gamma\delta^4$, respectively, yielding the mean power-law correlations $(1+z)\, E_p \propto [E_{\gamma,iso}]^{0.5\pm0.17}$, $(1+z)\, E_p \propto [L_{p,\gamma}]^{0.325\pm0.075}$, and $L_{p,\gamma} \propto [E_{\gamma,iso}]^{0.675\pm0.075}$. For the time-integrated γ-ray emission in multi-peak GRBs, the CB model predicts for single peaks and for the entire GRB, roughly the same power-law index ≈ 0.5 for the $E'_p - E_{\gamma,iso}$ correlation. However, since the duration of the prompt emission in multi-peak GRBs is independent of γ and δ, the mean luminosity $< L >$ (during T50 or T90) in such GRBs satisfies $E_{\gamma,iso} \propto < L >$ and $(1+z)\, E_p \propto < L >^{0.5\pm0.17}$. If $L_{p,\gamma} \propto < L >$, then the last correlation is valid also for the peak luminosity of the entire GRB, i.e., $E_{\gamma,iso} \propto L_{p,\gamma}$. The above CB model correlations which were predicted (Dar & De Rújula 2000, 2004) *before* their empirical discovery (Amati et al. 2002; Yonetoku et al. 2004) are well satisfied by GRBs as shown in Figs. 1-3.

5. The total energy of the prompt X-ray emission

In the CB model, the prompt γ and X-ray emission is dominated by ICS of thin thermal bremsstrhalung (Dar & De Rújula 2004). Its time integrated spectrum is given roughly by an exponentially cut-off power-law (CPL), $\int E\,(dn/dE)\,dt \sim E^{1-\alpha}\, e^{-E/E_p}$, where $\alpha \approx 1$ and then the 'cut-off' energy E_c is roughly E_p, the peak energy of $E^2 \int (dn/dE)\,dt$. Consequently, for the X-ray band which is usually well below E_p, the emitted prompt X-ray energy, within a band width ΔE is given by

$$E_{X,prompt} \approx \frac{\Delta E}{E_p}\, E_{\gamma,iso}\,, \tag{1}$$

where $E_{\gamma,iso}$ is the prompt gamma ray energy emitted under the assumption of isotropic emission. Using the CB model relations (Dar & De Rújula 2000,2004), $E'_p \propto \gamma_0\,\delta_0$ and $E_{\gamma,iso} \propto \delta_0^3$, one obtains $E_{X,prompt} \propto \delta_0^2/\gamma_0$.

If the X-ray energy $E_{1,X}$ emitted during the first phase of the X-ray light curve measured by the Swift/XRT is proportional to $E_{X,prompt}$, then Eq. (1) implies that $E_{1,X} \propto [E_{\gamma,iso}]^{0.5\pm0.17}$, in agreement with the correlation $E_{1,X} \propto [E_{\gamma,iso}]^{0.62\pm0.04}$ reported in Margutti et al. 2013).

6. The X-ray afterglow in the CB Model

In the CB model, the GRB afterglow begins when the CB has crossed the glory light and entered the circumburst wind, which had been ejected by the progenitor star. The circumburst medium in front of the highly relativistic CB is completely ionized by its radiation. In the CB's rest frame, the ions of the medium that are continuously impinging on the CB generate within it a turbulent magnetic field, which is assumed to be in approximate energy equipartition with them. The electrons that enter the CB are Fermi accelerated and cool rapidly by synchrotron radiation (SR). This SR is isotropic in the CB's rest frame and has a smoothly broken power-law with a characteristic injection bend/break frequency, which is the typical synchrotron frequency radiated by the interstellar medium (ISM) electrons that enter the CB at time t with a relative Lorentz factor $\gamma(t)$. In the observer frame, the emitted photons are beamed into a narrow cone along the CB's direction of motion by its highly relativistic bulk motion, their arrival times are aberrated and their energies are boosted by its bulk motion Doppler factor δ and redshifted by the cosmic expansion during their travel time to the observer.

The spectral energy density of the *unabsorbed* X-ray afterglow of a single CB has the form (see, e.g., Eq. (26) in Dado et al. 2009a),

$$F_\nu \propto n^{(\beta_X+1)/2}\,[\gamma(t)]^{3\,\beta_X-1}\,[\delta(t)]^{\beta_X+3}\,\nu^{-\beta_X}\,, \tag{2}$$

where n is the baryon density of the medium, $\delta\!=\!1/\gamma\,(1\!-\!\beta\,cos\theta)$ is the CB's Doppler factor with θ being the angle between the line of sight to the CB and its direction of motion, and $\beta_X+1=\Gamma_X$ is the photon spectral index of the emitted (unabsorbed) radiation. For $\gamma^2\gg 1$ and $\theta^2\ll 1$, $\delta\approx 2\,\gamma/(1\!+\!\gamma^2\,\theta^2)$ to an excellent approximation. The X-ray band is well above the break frequency, where typically $\Gamma_X\approx 2$, i.e., $\beta_X\simeq 1$, and Eq. (4) yields $F_\nu\propto n\,[\gamma]^2\,[\delta]^4\,\nu^{-1}$. For a 'shot-gun' configuration of CBs, Eq. (2) yields (Dado and Dar 2012b)

$$F_\nu \propto n^{(\beta_X+1)/2}\,[\gamma(t)]^{4\,\beta_X}\,\nu^{-\beta_X}\,, \tag{3}$$

which reduces to $F_\nu\propto n\,[\gamma]^4\,\nu^{-1}$ for $\beta_X\simeq 1$.

6.1. The initial and break-time luminosities of canonical AGs

The intercepted ISM particles that are swept into the CB decelerate its motion. For a CB of a baryon number $N_{_B}$, a radius R and an initial Lorentz factor $\gamma_0=\gamma(0)\gg 1$, which propagates in an ISM of *a constant density* n, relativistic energy-momentum conservation

($M(t)\,\gamma(t) \approx M_0\gamma_0$ where $M_0 = M(0)$) implies

$$(M_0\,\gamma_0/\gamma(t))\,d\gamma = -\pi\,R^2\,n\,m_p\,[\gamma(t)]^3\delta(t)\,c\,dt/(1+z)\,, \tag{4}$$

which yields the deceleration law (Dado et al. 2009b and references therein)

$$\gamma(t) = \frac{\gamma_0}{[\sqrt{(1+\theta^2\,\gamma_0^2)^2 + t/t_0} - \theta^2\,\gamma_0^2]^{1/2}}\,, \tag{5}$$

where $t_0 = (1+z)\,N_{\rm B}/8\,c\,n\,\pi\,R^2\,\gamma_0^3\,.$

As long as $t \lesssim t_b = (1+\gamma_0^2\theta^2)^2\,t_0$, $\gamma(t)$ and $\delta(t)$ change rather slowly with t, which generates the plateau phase of $F_\nu(t)$ of canonical X-ray AGs that was predicted by the CB model (see, e.g., Dado et al. 2002, Figs. 27-33) and later observed with Swift (Nousek et al. 2006, Panaitescu et al. 2006, Zhang et al. 2006). For $\beta_X \simeq 1$, the X-ray luminosity at the beginning time t_i of the plateau phase that follows from Eq. (2) is given by $L_X(t_i) \propto \gamma_0^2\,\delta_0^4$. From Eq. (5) it follows that for $t \gg t_b$, $\gamma(t) \to \gamma_0(t/t_b)^{-1/4}$, $[\gamma(t)\theta]^2$ becomes $\ll 1$ and $\delta \approx 2\,\gamma(t)$ which result in a late-time power-law decay

$$F_\nu(t) \propto [\gamma_0]^{4\,\beta_X+2}\,(t/t_b)^{-\beta_X-1/2}\,. \tag{6}$$

Hence, the dependence on the Doppler and Lorentz (L&D) factors of the break-time is $t_b \propto 1/\gamma_0\,\delta_0^2$, which yields the triple correlation

$$t_b \propto 1/E_p\,[E_{\gamma,iso}]^{1/3}. \tag{7}$$

Then, the substitution $t_b = (1+z)\,t'_b$ and $E'_p \propto [E_{\gamma,iso}]^{1/2}$ yields the approximate pair correlation

$$t_b/(1+z) \propto [E_{\gamma,iso}]^{-5/6}\,. \tag{8}$$

The late-time power-law behaviour of F_ν extrapolated back to $t = t_b$ yields $L_X(t_b) \propto [\gamma_0\,\delta_0]^3 \propto [E'_p]^3$. Note that the predicted late-time ($t' \gg t'_b$) behaviour of the X-ray luminosity at a fixed t',

$$L(t') \propto \gamma_0^{1.5}\,t'^{-1.5} \propto [E_{\gamma,iso}]^{0.5}\,t'^{-1.5}\,, \tag{9}$$

is in agreement with the observed behaviour $L_X(11h) \propto [E_{\gamma,iso}]^{0.50}$ (Margutti et al. 2013).

Note also that for a 'shot gun' configuration of CBs, $L_X(t_i) \propto \gamma_0^{4\,\beta_X}$ and $L_X(t \gg t_b) \propto \gamma_0^{4\,\beta_X}\,(t/t_b)^{-\beta_X}$ (Dado & Dar 2012b), and the late-time power-law behaviour of L_X extrapolated back to $t = t_b$ yields $L_X(t_b) \propto \gamma_0^{4\,\beta_X}$. Hence, for $\beta \simeq 1$, roughly $L_X(t_b) \propto L_X(t_i) \propto \gamma_0^{5\pm1}$.

The CB model (achromatic) break-time parameter t_b, however, is not the same as the chromatic break-time parameter of the phenomenological smooth broken power-law

parametrization used by Margutti et al. (2013) to parametrize canonical AGs. Consequently, the correlations satisfied by the CB model break-time of the X-ray AG may differ slightly from those inferred from the phenomenological broken power-law fits reported in Margutti et al. 2013.

6.2. $E_{2,X}$ in canonical GRBs

Assuming isotropic emission in the GRB 'rest frame' at redshift z (luminosity distance d_L), the total emitted energy during the afterglow phase in the rest frame X-ray band $[\nu'_1, \nu'_2]$ is given by

$$E_{X,iso} = \frac{4\,\pi\; d_L^2}{(1+z)} \int\int F_\nu(t)\,dt\,d\nu \tag{10}$$

where the ν integration is from $\nu_1 = \nu'_1/(1+z)$ to $\nu_2 = \nu'_2/(1+z)]$. Since $F_\nu \propto \nu^{-\beta_X} \sim \nu^{-1}$, the ν integration is practically independent of redshift. Moreover, Eq. (4) can be used to convert the time integration in Eq. (8) to integration over γ, yielding $E_{2,X} \propto \gamma_0^2\,\delta_0$ for the total energy emitted in the 0.3-30 keV X-ray band during the afterglow phase, assuming isotropic emission.

6.3. $E_{X,iso}$ and $E_{1,X}$ of canonical GRBs

Margutti et al. (2013) have defined $E_{1,X}$ and $E_{X,iso}$ to be the isotropic equivalent X-ray energy emitted in the 0.3-30 keV X-ray band during the first phase, and during the entire observations of the X-ray light-curve, respectively, with the Swift/XRT, respectively, which usually have begun some 60 seconds after the Swift/BAT trigger. In the CB model, however, each pulse in a multi-pulse GRB ends with a fast decline accompanied by a rapid spectral softening, which is taken over by a SR afterglow that has a more moderate temporal decay (a power-law index $\lesssim$2) and a *constant*, much harder, spectral index ($\beta_X \approx 1$). If that is correct, the AG in multipulse GRBs begins during the fast decline of the first prompt emission pulse and $E_{X,iso}$ as defined in Margutti et al. 2013 may miss a considerable fraction of the emitted X-ray energy. This can be verified by extrapolating the prompt γ-ray spectrum measured with the Swift broad area telescope (BAT) or the Fermi gamma-ray burst monitor (GBM) to the 0.3-10 keV band. A rough comparison of the CB model predictions for the correlations satisfied by $E_1(X)$ and $E_{X,iso}$ in Margutti et al. 2013, can be obtained by adopting the observed $E_{1,X} - E_{X,iso}$ and $E_{X,iso} - E_{\gamma,iso}$ correlations and then using the CB model correlations satisfied by $E_{\gamma,iso}$ to predict the corresponding ones satisfied by $E_1(X)$ and $E_{X,iso}$.

7. Comparison with observations

7.1. Binary correlations

Table 1 summarizes the dependence of γ-ray and X-ray properties on the bulk motion Lorentz and Doppler (L&D) factors of the CBs in the CB model (see, e.g., Dar & Rújula 2000,2004 for the γ-ray properties, and Dado et al. 2002,2009a,b for the X-ray properties, respectively). In the table, we have used the notation E'_p and L_p for the rest frame peak gamma ray energy and the peak luminosity, respectively, during the prompt γ-ray emission.

Figs. 1-3 present our best fitted power-laws for the $E'_p - E_{\gamma,iso}$, $E'_p - L_p$, and $L_p - E_{\gamma,iso}$ correlations for a sample of 96 GRBs with known redshift, which was compiled by Yonetoku et al. (2010). Using essentially the method advocated by D'Agostini (2005) we obtained the best fit correlations $(1+z)E_p \propto [E_{\gamma,iso}]^{0.526}$, $(1+z)E_p \propto [L_{p,\gamma}]^{0.532}$, and $L_{p,\gamma} \propto [E_{\gamma,iso}]^{1.13}$ in good agreement with those predicted by the CB model. Note that the correlations satisfied by E_p imply that $E_{\gamma,iso} \propto [L_p]^{1.01}$. The $\sim 10\%$ difference in the power-law index of the $E_{\gamma,iso} - L_p$ correlation, probably provides a realistic estimate of the accuracy of the indexes extracted from the observational data. The pair correlations reported in Table 4 of Margutti et al. 2013 contain, however, some puzzling inconsistencies which imply much larger errors. For instance, using their notation, in the limit of small dispersions their fitted correlations for long GRBs, $E_{1,X} \propto [E_{\gamma,iso}]^{0.63\pm0.04}$ and $E_{2,X} \propto [E_{\gamma,iso}]^{0.70\pm0.01}$ imply $E_{1,X} \propto [E_{2,X}]^{0.89\pm0.06}$, which is inconsistent with their reported correlation $E_{1,X} \propto [E_{2,X}]^{0.48\pm0.02}$.
Their fitted correlations $L_f \propto [L_{pk}]^{0.89\pm0.03}$ and $L_f \propto [t_f]^{-1.21\pm0.03}$ imply $t_f \propto [L_{pk}]^{-0.73\pm0.03}$, inconsistent with their reported correlation $t_f \propto [L_{pk}]^{-0.27\pm0.02}$.
Their fitted correlations $L_f \propto [L_{pk}]^{0.89\pm0.03}$ and $t_f^{RF} \propto [L_{pk}]^{-0.27\pm0.02}$ imply $L_f \propto [t_f^{RF}]^{-3.3\pm0.30}$, inconsistent with their reported correlation $L_f \propto [t_f^{RF}]^{-1.21\pm0.03}$.

Suspecting that such discrepancies result from the inclusion of peculiar GRBs such as 060218 in their fitted GRB sample and from misinterpretation of very late breaks in the afterglow of few energetic GRBs, such as 080329B, as the jet break (rather than due to density drop), we have examined the effect of removing GRB060218 from the sample of ordinary long GRBs of known redshift and replacing their chosen late break of the canonical afterglow of GRB 080329B by its first break. The resulting correlations are compared in Table 2 with the original correlations reported in Table 4 of Margutti et al. 2013. As can be seen from Table 2, the above modifications have changed significantly many correlations. Moreover, the inconsistencies between the correlations, have been largely reduced. E.g., the modified $E_{1,X} - E_{\gamma,iso}$ and $E_{2,X} - E_{\gamma,iso}$ correlations imply $E_{1,X} \propto [E_{2,X}]^{0.73}$ compared to $E_{1,X} \propto [E_{2,X}]^{0.56}$, the modified correlations $L_f - L_p$ and $L_f - t_f$ imply $t_f \propto [L_p]^{-0.60}$ compared to $t_f \propto [L_p]^{-0.71}$ and the modified correlations $L_f - L_p$ and $t_f^{RF} - L_p$ imply $L_f \propto [t_f^{RF}]^{-1.70}$

compared to $L_f \propto [t_f^{RF}]^{-1.71}$.

Table 3 compares the approximate power-law correlations between the γ-ray and X-ray propreties of long GRBs that are expected in the CB model (upper raws) from their dependence on the L&D factors and those extracted in the limit of small dispersions from the correlations reported in Margutti et al. 2013 (lower raws) after removing the peculiar GRB 060218 from their sample of long GRBs with known redshift and after changing the canonical break-time of GRB03029 to be its first break (see Table 2). As can be seen from Table 3, the correlations predicted by the CB model agree well with those obtained after the above modifications, which improve significantly the consistency between the correlations inferred directly from the data and those derived from them under the assumption of small dispersions.

7.2. The triple correlation $E_{X,iso} - E_{\gamma,iso} - E'_p$

A triple correlation $E_{X,iso} \propto (E_{\gamma,iso})^{1.06\pm0.06}/[E'_p]^{0.74\pm0.10}$ was found by Bernardini et al. (2012) to be well satisfied by both long and short GRBs. This correlation was updated in Margutti et al. (2013) to be $E_{X,iso} \propto (E_{\gamma,iso})^{1.00\pm0.06}/[E'_p]^{0.60\pm0.10}$. In the CB model, such triple correlations that unite LGRBs and SHBs are simple combination of corresponding binary power-law correlations of kinematic origin satisfied by LGRBs and SHBs (with the same index but different normalization). In particular, the above triple correlation is a simple consequence of the correlation $E'_p \propto [E_{\gamma,iso}]^k$ (that is shown in Fig. 1 for LGRBs with the current best fit value $k = 0.526$) that was predicted by the CB model to be satisfied both by LGRBs (e.g. Dar and De Rújula 2000,2004) and by SHBs (Dado et al. 2009b, Fig. 5) and the pair correlation $E_{X,iso} \propto [E_{\gamma,iso}]^{0.67\pm0.01}$ that was discovered by Margutti et al. (2013) for LGRBs. To see that, let us rewrite the $E_{X,iso} - E_{\gamma,iso}$ correlation that was found by Margutti et al. (2013) for LGRBs in the form

$$E_{X,iso} \propto [E_{\gamma\, iso}]^{0.67}\, \frac{[E_{\gamma\, iso}]^m}{[E'_p]^{m/k}}\,. \tag{11}$$

where the second factor on the right hand side (RHS) is a constant. For the triple correlation reported by Margutti et al. (2003), their best fit implies $m = 0.33 \pm 0.06$ and $m/k = 0.60 \pm 0.10$, which yield $k = (0.33 \pm 0.06)/(0.60 \pm 0.10) = 0.55 \pm 0.07$. The best fit values reported by Bernardini et al. (2012) yield $m = 0.39 \pm 0.06$ and $m/k = 0.74 \pm 0.10$, which implies $k = (0.39 \pm 0.06)/(0.74 \pm 0.10) = 0.527 \pm 0.05$. Both values are consistent with the CB model prediction $k \approx 0.5$ and with $k = 0.526$ obtained from the best fit shown in Fig. 1. For LGRBs, the triple correlation as written in Eq. (11) isindependent of the choice of an m value. However, in the CB model the power-law indexes of kinematic correlations are

common to SHBs and LGRBs. Thus, the value of m can be adjusted such that the triple correlation in LGRBs is satisfied also by SHBs.

7.3. The triple correlation $t_b - E_p - E_{\gamma,iso}$

As explained in section 3, the strong dependence of GRB observables on both the Lorentz factor and Doppler factor of the jetted CBs yield triple-correlations among these observables that can be reduced to binary correlations only with additional assumptions. We demonstrate that for an important case - the triple correlation $t_b - E_p - E_{\gamma,iso}$ as summarized in Eq. (7). This important correlation is based on the decelaration origin of the break in the canonical afterglow of the CB model. In Fig. 4, this correlation is compared with observations of 54 Swift GRBs/XRFs with known redshift, good temporal coverage of their X-ray afterglow during the first day (or more) following the prompt emission phase, and well measured E_p and $E_{\gamma,iso}$ with Konus-WIND and/or Fermi GBM. In order not to bias the values of t_b, E_p and $E_{\gamma,iso}$ by CB model fits, the break times were taken to be the times of the first break with $\alpha(t < t_b) < \alpha(t > t_b)$ obtained from the broken power-law fit to the GRB X-ray afterglow measured with the Swift/XRT and reported in the Leicester XRT GRB Catalogue (Evans et al. 2009) or from the smoothly broken power-law fit of Margutti et al. (2013). The values of $E_{p,\gamma}$ and $E_{\gamma,iso}$ were adopted from communications of the Konus-Wind and Fermi GBM collaborations to the GCN Circulars Archive (Barthelmy 1997), and from publications by Amati et al. (2007, 2008), Yonetoku et al. (2010), Gruber et al. (2011), Nava et al. (2012) and D'Avanzo et al.(2012). As shown in Fig. 4 the triple correlations predicted by the CB model is well satisfied by the observational data (the best fit power-law $t_b \propto 1/(E_p\,[E_{\gamma,iso}]^{1/3})^k$ yield $k = -1.19$ and χ^2 very similar to that obtained for the predicted power-law with $k = -1$.

The binary correlation $t_b/(1+z) \propto [E_{\gamma,iso}]^{-5/6\pm1/6}$ that was obtained by substituting the CB model correlation $E_{p,\gamma} \propto E_{\gamma,iso}^{1/2\pm1/6}$ in the triple correlation (Eq. 7) is shown in Fig. 5. It is also well satisfied by the observational data. The best fit power-law index -0.69 is in agreement with -0.83 ± 0.17 predicted by the CB model. In particular, the $t'_b - E_{iso}$ correlation implies that GRBs with very large $E_{\gamma,iso}$ ($\gg 10^{53}$ erg) have a small t'_b, which, probably, is hidden under the tail of the prompt emission or precedes the start of the XRT observations (Dado et al. 2007). Indeed, the X-ray afterglow of all the GRBs in our sample, which have a very large $E_{\gamma,iso}$, have a power-law decline consistent with the post break power-law decline predicted by the CB model (see, e.g., Dado et al. 2007, 2009a). For such GRBs, the observations provide only upper bounds on the break time of their X-ray afterglow that are indicated by down arrows in Figs. 4,5.

8. Discussion

A major breakthrough in the study of gamma ray bursts (GRBs) was the discovery of their X-ray afterglows by the Beppo-SAX satellite (Costa et al. 1997) that allowed their arcminute localization and consequently the discovery of their longer wave-length afterglows (van Paradijs et al. 1997, Frail and Kulkarni 1997), which were predicted (Paczynski and Roads 1993, Katz 1994, Mezaros and Rees 1997) by the fireball model (FB) of GRBs (Paczynski 1986, Goodman 1986). Consequently, the fireball model was widely accepted as the correct model of GRBs and their afterglows (e.g., Meszaros 2002, Zhang and Meszaros 2004, Piran 2004). The rich data on GRBs and their afterglows obtained in recent years with the Swift and Fermi satellites complemented by data from ground-based rapid response telescopes and large follow-up telescopes, however, have challenged this prevailing view (e.g., Margutti et al. 2013 and references therein, Godet & Mochkovitch 2012 and references therein).

In contrast to the FB model, the cannonball model (CB) of GRBs has been very successful in predicting the general properties of the prompt emission and afterglows of both long and short GRBs and in reproducing their detailed light-curves (e.g., Dado et al. 2009a,b and references therein). This success was despite the apparently different origins and environments of long GRBs and SHBs. But, it involved an adjustment of free parameters, which could have made one wonder whether the agreement between theory and observations was due to the flexibility of the model rather than its validity. Many properties of GRBs and correlations among GRB properties which are predicted by the CB model, however, do not involve adjustable parameters and thus enable more stringent tests of the model. So far the CB model was able to predict correctly all the main established correlations among GRB observables (see, e.g., Dar and De Rújula 2000,2004, Dado and Dar 2012a,b and references therein) including the newly discovered correlations (Liang et al. 2010) among and between the prompt γ-ray and optical properties of GRBs (e.g., Dado and Dar 2012a and references therein). In this paper we have shown that the CB model predicts correctly also the newly discovered correlations between their γ-ray and X-ray properties (Margutti et al. 2013, Bernardini et al. 2012). In particular, the correlations satisfied by the afterglow break time are those predicted by the CB model, and probably have nothing to do with an alleged opening angle of an hypothetical conical jet so called 'conical fireball'.

We have also shown that the triple correlation $E_{X,iso} - E_{\gamma,iso} - E'_p$ that is satisfied by both LGRBs and SHBs (Bernardini et al. 2012, Margutti et al. 2013) probably is a simple consequence of the fact that the binary power-law correlations $E_{X,iso} - E_{\gamma,iso}$ and $E'_p - E_{\gamma,iso}$ are satisfied by both LGRBs and SHBs with roughly the same power-law index and different normalizations, as expected in the CB model.

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Table 1. The dependence on Lorentz and Doppler factors of LGRB properties in the CB model

property:	$E_{1,X}$	$E_{2,X}$	$L_X(t_i)$	$L_X(t'_b)$	t'_b	$E_{\gamma,iso}$	E'_{pk}	$< L90 >$
$\propto$:	δ_0^2/γ_0	$\gamma_0^2\,\delta_0$	$\gamma_0^2\,\delta_0^4$	$\gamma_0^3\,\delta_0^3$	$1/\gamma_0\,\delta_0^2$	δ_0^3	$\gamma_0\,\delta_0$	δ_0^3

Table 2. Comparison between the power-law index m of the correlations $Y \propto X^m$ inferred in Margutti et al. 2013 for various properties X and Y of long duration GRBs of known redshift observed with the Swift/XRT and those inferred by us from the correlations found by Margutti et al. (2013) after removing the peculiar GRB 060218 from the GRB sample and after correcting the canonical break-time of GRB 080319B to be its first break.

X	Y	m (Margutti)	m (corrected)
$E_{X,iso}$	L_f	1.29	1.40
$E_{X,iso}$	L_i	1.49	
t_f^{RF}	L_f	-1.21	-1.71
L_f	$E_{2,X}$	0.52	0.52
$E_{2,X}$	$E_{1,X}$	0.48	0.56
$E_{\gamma,iso}$	$E_{X,iso}$	0.66	0.66
$E_{\gamma,iso}$	$E_{1,X}$	0.62	0.60
$E_{\gamma,iso}$	$E_{2,X}$	0.70	0.70
$E_{\gamma,iso}$	L_f	1.06	1.60
E_{pk}	$E_{X,iso}$	0.96	1.15
L_{pk}	L_f	0.89	1.25
L_{pk}	t_f^{RF}	-0.27	-0.51
L_{pk}	$E_{2,X}$	0.60	0.60
L_{pk}	$E_{X,iso}$	0.47	0.61

Table 3. Comparison between the power-law index m of the correlations $Y \propto X^m$ predicted by the CB model (upper raws) for various pairs (X, Y) of properties of long duration GRBs and those inferred (lower raws) from the correlations reported in Margutti et al. 2013 after excluding from the fits GRB 060218 and replacing the break time and break time luminosity of GRB080319B by those of the first break.

Y	$E_{2,X}$	$L_X(t'_i)$	$L_X(t'_b)$	$t'_{b,X}$	$E_{\gamma,iso}$	E'_p	L_p
$E_{2,X}$	1	0.50	0.50	-1	$0.67 \pm .33$	$1.25 \pm .25$	$0.43 \pm .17$
	1	0.50	0.52	-0.93	0.70	1.27	0.60
$L_X(t'_i)$	2	1	1	-2	$1.67 \pm .33$	$2.33 \pm .33$	1.20
	$1.5 \pm .5$	1	1.05	-1.52	1.52	2.71	1.31
$L_X(t'_b)$	2	1	1	$-1.75 \pm .25$	$1.50 \pm .50$	3	$1.5 \pm .50$
	1.71	0.95	1	-1.71	1.06	2.02	1.06
t'_b	-1.	-0.50	$-0.58 \pm .08$	1	-0.83 $\pm$ .17	-1.67 $\pm$ .33	$-0.83 \pm .17$
	-1.07	-.66	-0.63	1	-0.69	-1.38	-0.61
$E_{\gamma,iso}$	1.50	$0.63 \pm .13$	$0.63 \pm .13$	$-1.25 \pm .25$	1	$2 \pm .5$	1.
	1.43	0.66	0.63	-1.45	1	1.90	0.88
E'_p	$0.83 \pm .17$	$0.29 \pm .04$	$0.29 \pm .04$	-0.58 $\pm$ .08	$0.50 \pm .17$	1	$0.50 \pm .17$
	0.78	0.37	0.36	0.56	0.53	1	0.52
L_p	1.67	0.83	0.83	-1.67	1.	2.0 ± 0.33	1
	1.59	0.76	0.80	-1.43	1.13	2.14	1

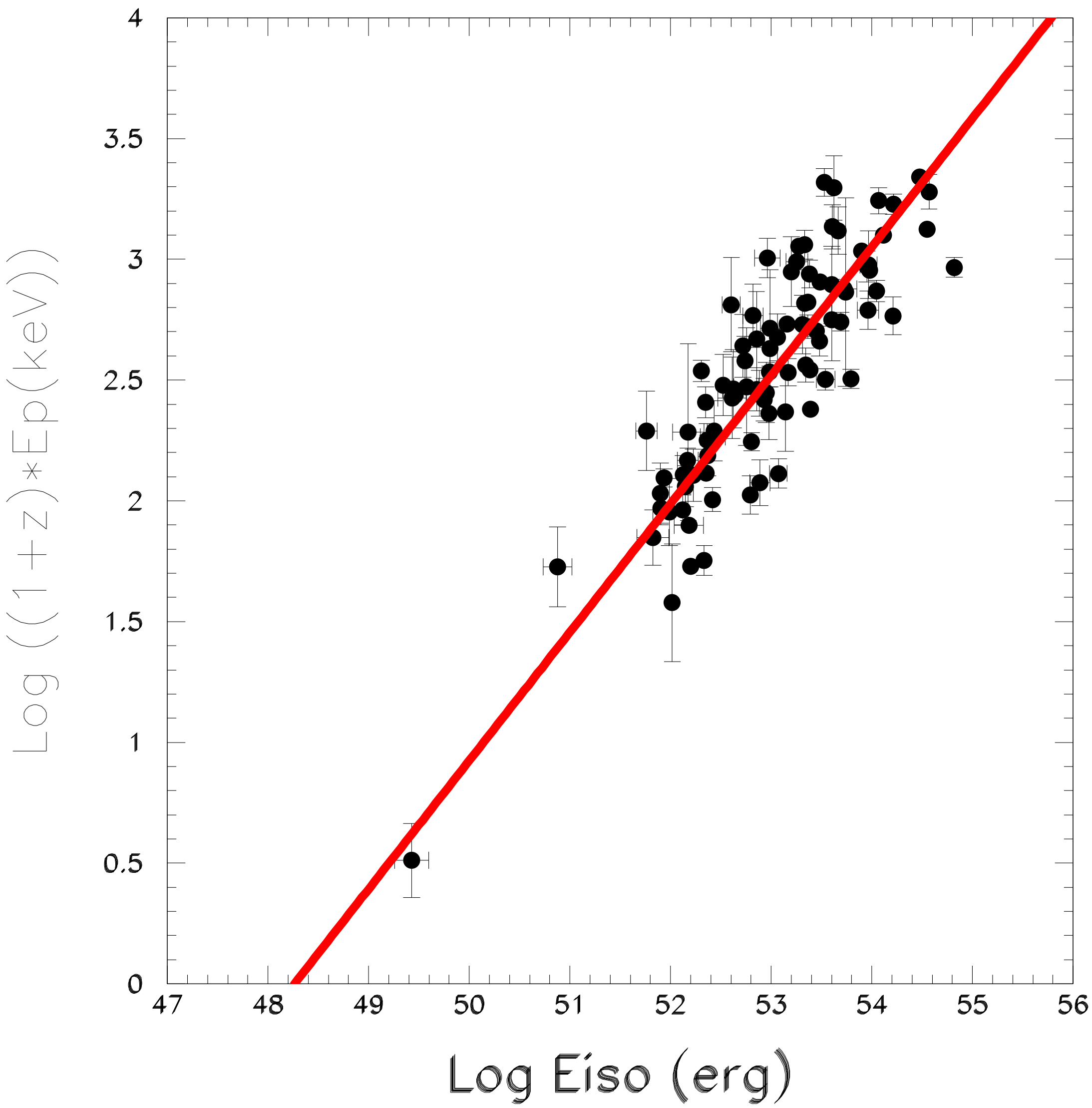

Fig. 1.— The observed correlation between $(1+z)\,E_p$ and $E_{\gamma,iso}$ for 96 GRBs with known redshift compiled by Yonetoku et al. (2010). The best fit power-law correlation (straight line) has a power-law index 0.532 .

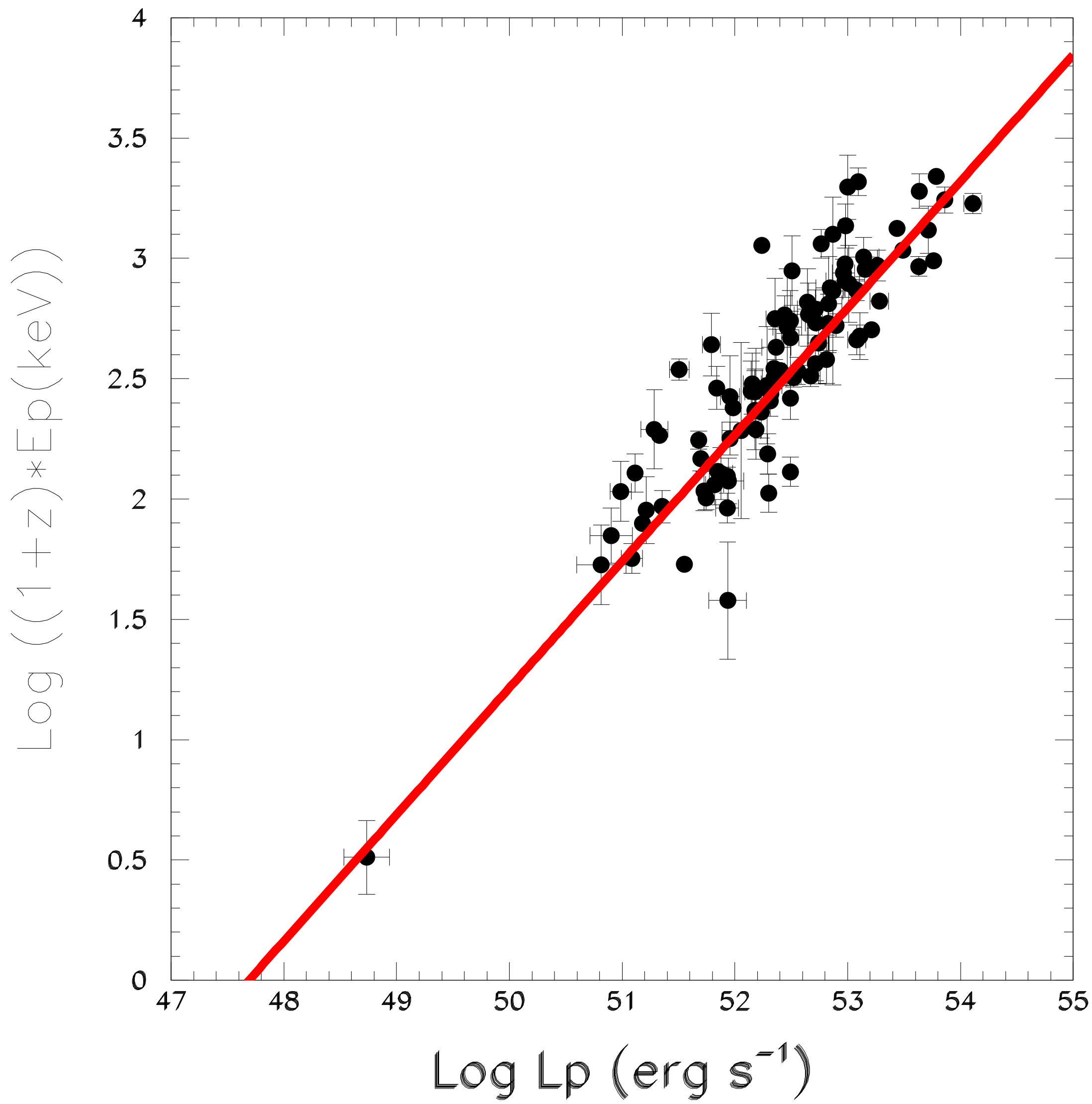

Fig. 2.— The observed correlation between $(1 + z)\, E_p$ and $L_{p,\gamma}$ for 96 GRBs with known redshift compiled by Yonetoku et al. (2010). The best fit power-law correlation (straight line) has a power-law index 0.526 .

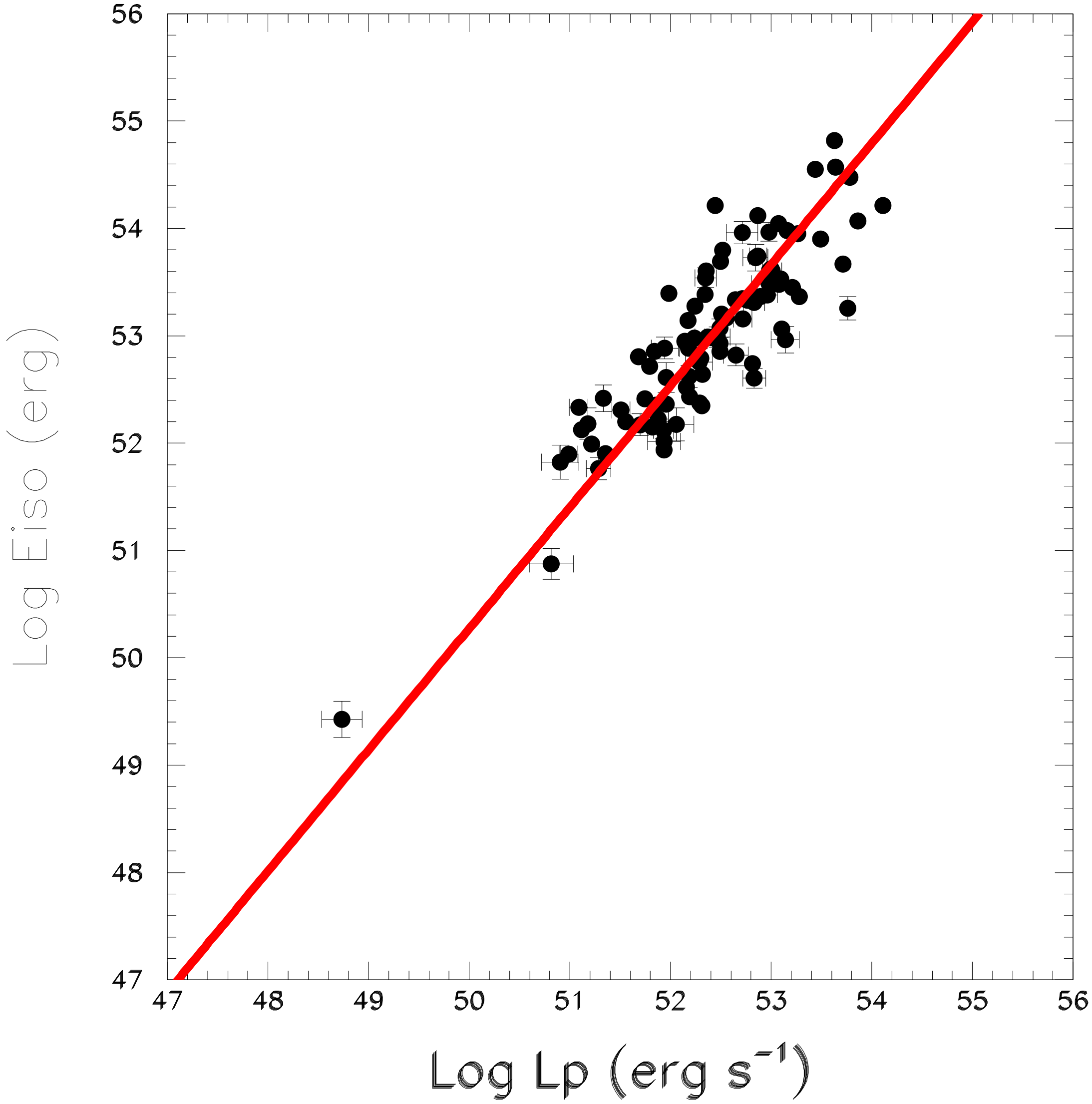

Fig. 3.— The observed correlation between $E_{\gamma,iso}$ and $L_{p,\gamma}$ for 96 GRBs with known redshift compiled by Yonetoku et al. (2010). The best fit power-law correlation (straight line) has a power-law index 1.13 .

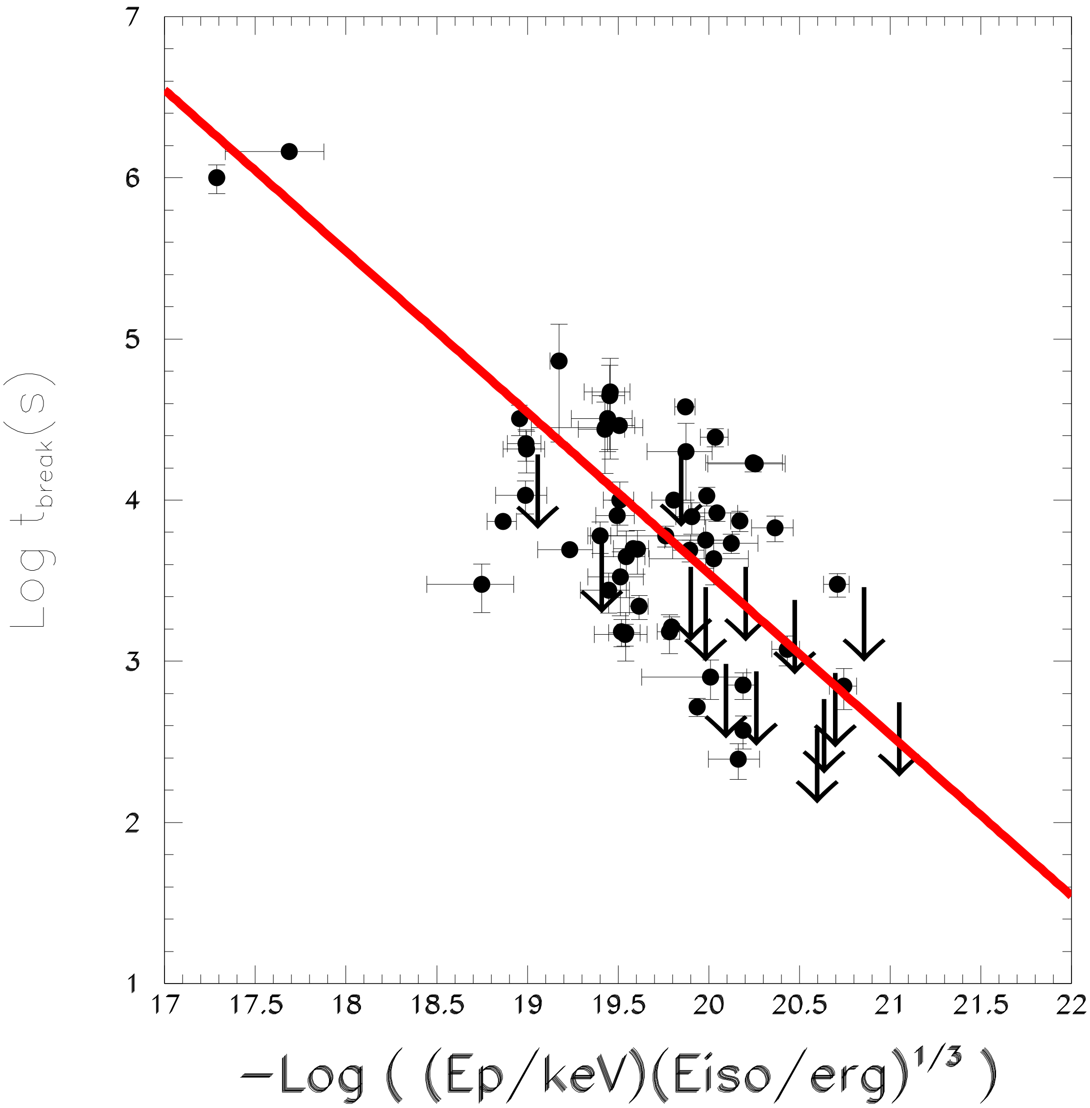

Fig. 4.— Comarison between the triple correlations $t_b - E_p, -E_{\gamma,iso}$ predicted by the CB model (Eq. 7) and that observed in 53 Swift GRBs with measured redshift, t_b', E_p' and $E_{\gamma,iso}$. Arrows indicate observational upper bounds on early-time deceleration breaks hidden under the prompt emission tail.

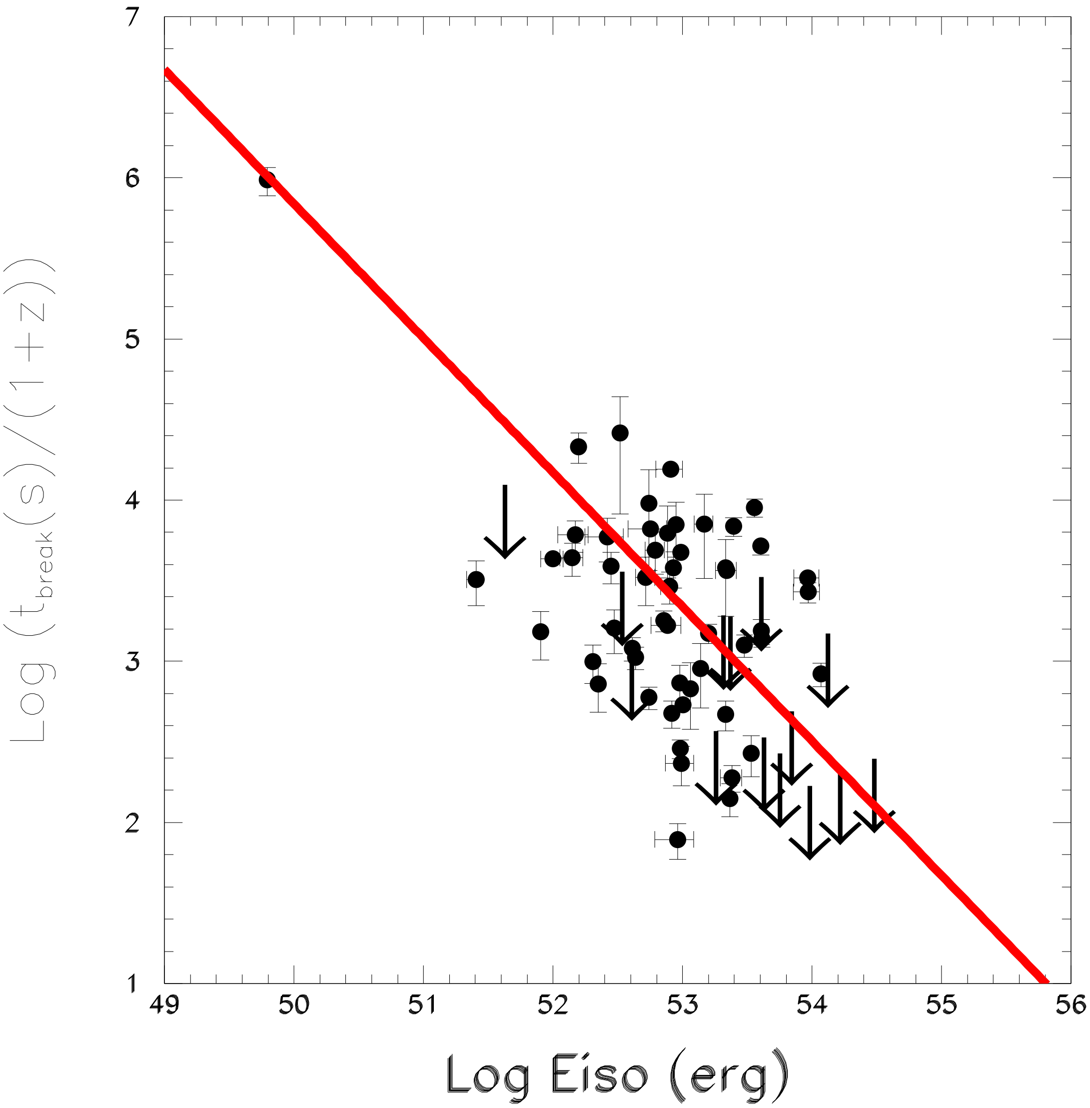

Fig. 5.— Comarison between the binary correlation $t_b/(1+z) - E_{\gamma,iso}$ predicted by the CB model (Eq. 8) and that observed in 53 Swift GRBs with measured redshift, t_b and $E_{\gamma,iso}$. Arrows indicate observational upper bounds on early time deceleration breaks hidden under the prompt emission tail.